LA-UR -82-1240

Conf-820249--1

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

LA-UR--82-1240

DE82 015767

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SUBMITTED TO: AIP Conference Proceedings
American Institute of Physics
335 E. 45th St.
New York, NY 10017

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FORM NO 836 R4
ST NO 2629 5/81

ARE GRATINGS INVISIBLE?

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ABSTRACT

I show that laser grating accelerators may encounter serious difficulties in operating near or even below the damage threshold caused by the formation of a dense plasma above the grating, which obscures the grating shape.

INTRODUCTION

The possibility of accelerating particles in the near field of laser light incident on a grating has been widely discussed.[1] The potentially high gradients and small volume of field make this scheme attractive both from the viewpoint of total accelerator length and from the viewpoint of stored energy. Two modes of operation have been envisaged: in one mode the incident field is kept below the damage threshold, and the grating is used for many laser pulses; in the other mode the grating is destroyed and then replaced after each laser pulse. I want to point out in this paper that, depending on laser pulse length, grating material, and grating purity, there may be significant limitations on operating near, or even below the damage threshold.

DISCUSSION

First let us observe that if a plasma of critical density, N_c, exists above the grating then the grating is effectively invisible. The critical density is that at which the plasma frequency equals the laser frequency and is given by

$$N_c = \frac{M_e \omega^2}{4\pi e^2} , \tag{1}$$

where M_e is the electron mass, ω is 2π times the laser frequency, and e is the electron charge. I will show that under certain conditions such a plasma does exist above gratings.

Certainly near, and possibly below, the damage threshold significant amounts of material will be boiled or sublimed off the grating surface. To form a plasma of critical density for a grating appropriate to a CO_2 laser (10.6 μm) requires only $\sim$10 Å of material to be evaporated. I will assume that this material exists as a plasma just above the grating, that is, that the ionization time is very short.

Once the material is ionized it can no longer stream freely into the whole volume; the individual particles oscillate in the electric field with very small radial excursions. A plasma confined very near the grating surface would have little effect on accelerator operation.

If the plasma density were high enough and the temperature low enough, the electron collision time would be at the subpicosecond level; one might imagine that collisions would spread out the plasma. However, the development of strong space charge forces would freeze the electrons onto the ions and reduce the diffusion rate to that of the ions; this would be a significant process only on the microsecond time scale.

I want to point out, however, that a purely collisionless process exists that will rapidly spread the plasma uniformly over the grating. A crude picture of the grating geometry and field lines is shown in Fig. 1. There are two important points to be noted from this figure. First, the plasma need only spread a distance $\lambda/8$, where λ is the laser wavelength, to be uniform. Second, the electric field strength is not spatially uniform; indeed, for purposes of acceleration, it could not be.

When a particle is in a rapidly oscillating nonuniform field it "sees" an effective potential given by[2]

$$U_{eff} = \frac{e^2 E_0^2}{4m\omega^2} , \tag{2}$$

where E_0 is the field strength and m is the particle mass. Let us note that the effective force on the ions is much smaller than the force on the electrons; we will approximate the effective force on the ions by zero.

The electrons will be pulled toward the low-field region, but will be retarded once again by the space-charge force. To see what

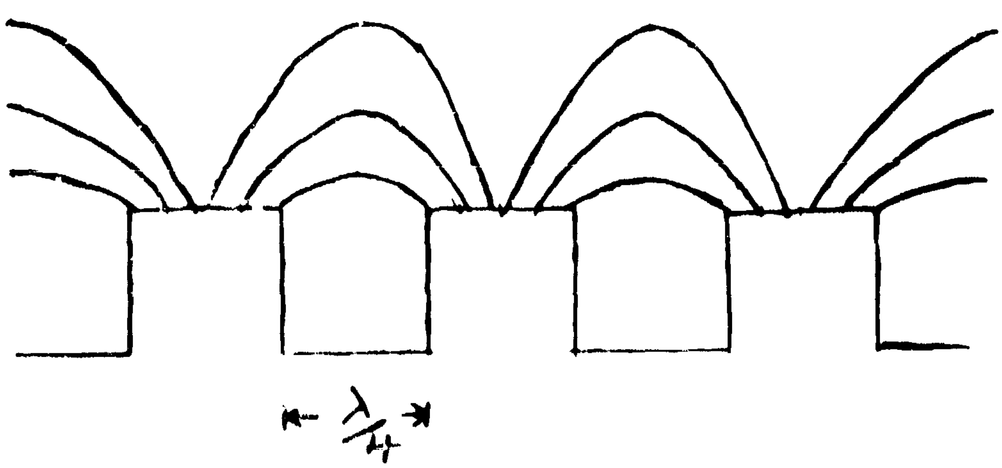

Fig. 1. Schematic of a grating accelerator with field lines shown.

will happen, let us write down the force equations for ions and electrons. These are

$$\frac{\partial \vec{V}_i}{\partial t} + \vec{V}_i \cdot \vec{\nabla}\vec{V}_i = \frac{e\vec{E}}{M_i} \quad , \tag{3}$$

$$\frac{\partial \vec{V}_e}{\partial t} + \vec{V}_e \cdot \vec{\nabla}\vec{V}_e = -\frac{e\vec{E}}{M_e} - \frac{\vec{\nabla}U_{eff}}{M_e} \quad , \tag{4}$$

where $\vec{E}$ is the space-charge field.

Though the initial dynamics is very complicated, the plasma will quickly approach a steady state flow. To avoid steady space-charge build-up in this steady state, the right-hand sides of Eqs. (3) and (4) must be equal. We thus find that

$$e\vec{E} = -\frac{M_i}{M_i + M_e}\vec{\nabla}U_{eff} \simeq -\vec{\nabla}U_{eff} \quad . \tag{5}$$

Thus, space charge communicates the electron force to the ions virtually unchanged.

The approximate time for uniform spreading is

$$T \simeq \sqrt{\frac{M_i \lambda^2}{24\, U_{eff}}} \quad . \tag{6}$$

Using Eq. (2), Eq. (6) can be rewritten as

$$T \simeq \frac{2\pi}{|eE_0|c}\sqrt{\frac{M_i c^2 M_e c^2}{6}} \quad . \tag{7}$$

The laser dwell time before particle arrival must be held significantly below the time given by Eq. (7). A table of T/3 in picoseconds for different fields and different ions is given below.

Table I Laser Dwell Times

E_0 (GeV/m)	H	O	Fe	Cu
1	62	248	464	492
5	12.4	49.6	92.8	98.4
10	6.2	24.8	46.4	49.2
20	3.1	12.4	23.2	24.6

Note that the accelerating gradient will be about $eE_0/2$.

CONCLUSIONS

To avoid significant field modifications the laser dwell time should be held to less than T/3. Because very high-power lasers with short, accurately timed pulses will require significant technological advances, the numbers given in the above table represent fairly stringent restrictions on the operation of a grating accelerator. In particular, we can draw the following conclusions.

- Gratings should be made of as heavy a material as possible.
- Surface contamination by light elements must be eliminated.
- Operation above the damage threshold is probably not possible with foreseeable technology.

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